

Coherent switching of semiconductor resonator solitons

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We demonstrate switching on and off of spatial solitons in a semiconductor microresonator by injection of light coherent with the background illumination. Evidence results that the formation of the solitons and their switching does not involve thermal processes.

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Spatial solitons in semiconductor resonators have recently been considered for applications as mobile binary information carriers for certain optical parallel information processing tasks [1,2]. We have recently found that such dark and bright spatial solitons can exist in nonlinear passive semiconductor resonators [3]. We demonstrated in [4] that bright solitons can be switched on (and also temporarily be switched off) by addressing with a light beam incoherent with the background light field, which sustains the solitons. In this case a light-induced increase of temperature [5] is involved in both switching on and off which limits the switching speed to typically $1 \mu\text{s}$.

An alternative mechanism of switching such solitons on or off is by changing the carrier density in the resonator at the location of the soliton. This can be effected by addressing the position of the soliton (to be created or to be switched off) with a sharply focused light beam coherent with the background light. The latter's intensity is to be within the coexistence range of soliton and low transmission resonator state. If the address beam is in phase with the background light the intensity at the soliton location will be increased when admitting the address beam. This increases the carrier density locally and therefore can switch a soliton on. Vice versa, an existing soliton can be switched off when the address beam is in counterphase to the background light. By destructive interference the light intensity at the location of the soliton can decrease below the existence range of solitons so that a soliton may be switched off.

In this coherent scheme primarily the changing of the local carrier density causes the switching, whereas in the incoherent scheme reported in [4] the increasing of the temperature causes the switching. Nonthermal incoherent switching can also be done - e.g. by application of local optical pumping [6] pulses which increase the carrier density. Nonetheless the coherent scheme is the only one permitting on- and off-switching in a straightforward manner [2,7-9]. We conducted therefore an experiment to demonstrate this mechanism.

Fig. 1 shows the optical arrangement used for the observations. Light of single frequency Ti:Al₂O₃-laser at 850 nm wavelength illuminates an area on the resonator sample of $\sim 50 \mu\text{m}$ diameter. Part of the light is split

away from the main beam and then superimposed with the main beam by a Mach-Zehnder interferometer arrangement, to serve as the address beam. In the address path of the interferometer the light is expanded so that the focus of the address beam is narrow ($\sim 8 \mu\text{m}$). An electro-optic modulator switches the address beam on for a short time ($\sim 40 \text{ ns}$). One of the interferometer mirrors can be moved by a piezo-electric element to control the phase difference between the background light and the address light.

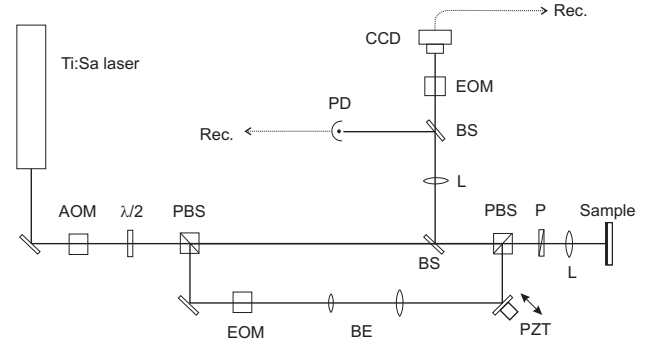


FIG. 1. Experimental setup.

AOM: acousto-optic modulator, $\lambda/2$: halfwave plate, PBS: polarizing beam splitters, EOM: electro-optical amplitude modulators, BE: beam expander, PZT: piezo-electric transducer, L: lenses, BS: beam splitters, PD: photodiode, P: polarizer. Polarizer P combines coherently the injection and background fields.

In order to avoid long-term thermal drifts the measurements are carried out within a few μs . The laser light is admitted through an acousto-optic modulator for durations of a few μs and repeated every ms. For observation a CCD-camera combined with an electro-optic modulator serves to take snapshots on a nanosecond timescale. The modulator opens with a variable delay after the start of the illumination so that snapshots can be taken at different times during the illumination. The dynamics is followed more directly locally by imaging a fast photodiode onto the center of one soliton on the resonator sample. The light intensity at the soliton location is then recorded as a function of time.

The semiconductor sample was a passive resonator

containing 12 GaAs quantum wells cladded by two Bragg reflector stacks consisting of 23 and 17 pairs of Al-GaAs/AlAs quarter-wave layers, respectively. The Bragg mirrors were designed to be non-absorptive above 810 nm. The resonator itself was a $3/2 \lambda$ resonator of the 'cos' type and the width of the GaAs quantum wells was 15 nm. Suitable spacers between the QW material and the Bragg stacks place the resonance wavelength of this resonator in the vicinity of the band gap at 850 nm. The radial thickness variation of the layers from the center to the edge of the circular 2 inch wafer causes a radial variation of the resonance wavelength of only 7 nm. This very good large-scale homogeneity allows to maintain the relative detuning of laser light to resonance center over large distances on the wafer. This kind of sample should therefore be well suited for experiments on motion of spatial solitons. The resonance wavelength everywhere on the wafer is close to (below) the band edge wavelength. Thus the nonlinearity is strongly absorptive.

Working at $\lambda = 850$ nm, bright spatial solitons are readily observable (Fig. 2); they form spontaneously or with addressing pulses. Figs. 3 and 4 show the results of the switching experiments. The dotted lines show the incident intensity and the solid line the intensity reflected from the sample. Note that the observation is in reflection such that a bright soliton (high transmission) shows up as a reduction in reflected intensity.



FIG. 2. Bright soliton (dark in reflection). 3D representation of reflectivity: a) view from above, b) view from below.

Fig. 3a shows the switch-on. The background intensity is chosen slightly below the spontaneous switching threshold. With the application of the in-phase address pulse the reflected light intensity increases (constructive interference) and the soliton is switched on (evidenced by the reduced reflectivity). Evidently the soliton remains switched on until the background light is reduced to the lower limit of the existence range of the soliton.

Fig. 3b shows a "failed switch" in which the intensity of the address beam is too low to switch. Equally to Fig. 3a the in-phase address pulse shows up as increased reflected light intensity, however, the total intensity at the address position does not reach the upper limit of the soliton existence range so that no soliton forms.

Fig. 3c shows the switching off of a soliton. The background light intensity is chosen above the coexistence

range of soliton and low transmission resonator state, so that a soliton forms spontaneously. The address beam is then applied in counter-phase to the background field (evident by a reduction of reflected light due to the destructive interference between background- and address light), the soliton disappears, and the resonator returns to the low transmission state. Fig. 3d shows a "failed switch-off" analogously to Fig. 3b.

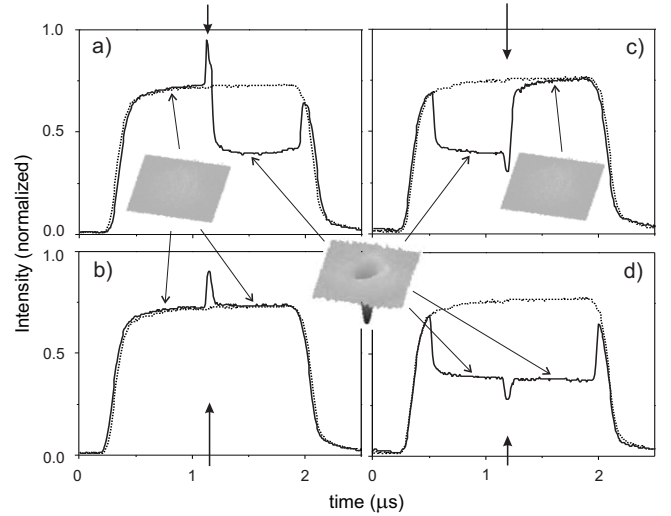


FIG. 3. Recording of switching-on (a)) and switching-off (c)) of a bright soliton. "Failed switches" with the address beam intensity too low to switch soliton on (b)) or off (d)). Heavy arrows mark the application of address pulses. Dotted traces: incident intensity. The insets show intensity snapshots, namely soliton (as Fig. 2a) and unswitched state.

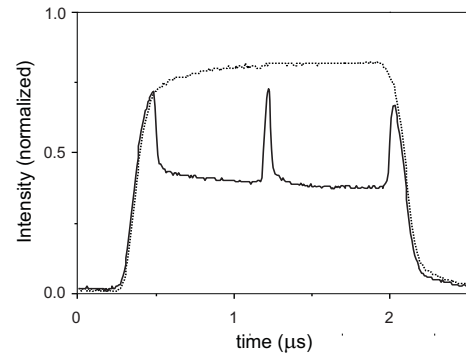


FIG. 4. Demonstration of the non-thermal character of soliton switching. As opposed to the incoherent switching [4], the soliton is stable against local increase of intensity. Dotted trace: incident intensity.

In Fig. 4 we demonstrate that the switching here is really primarily controlled by the light field in the resonator varying the carrier density rather than by temperature increase or generating of phonons as in the incoherent

case [4].

In [4] a soliton could be switched off by increasing locally the light intensity. The mechanism being that the additional carrier generation increased the lattice temperature, which shifts the band edge. With this the existence range of solitons shifted. The soliton therefore switched off and remained off until the lattice had cooled again. The address pulse was perpendicularly polarized to the background field, thus incoherent with it.

In Fig. 4 the intensity is also increased, but in a coherent way, by constructive interference with the (in-phase) address pulse. As opposed to [4] the intensity increase does not switch the soliton off, showing that a thermal shift of the existence range does not noticeably occur. Rather here the switching is controlled through the (fast) electronic nonlinearity.

This absence or negligibility of thermal effects in the formation of solitons is equally evidenced by the fast spontaneous switchings in Fig. 3. This nonthermal switching is in agreement with the experiments [10] where the working wavelength of the structure used was (equal to the structure grown for there present observations) slightly below the band edge.

The absence of the thermal effects in the soliton formation was related in [10] to the predominantly absorptive character of the nonlinearity. Here essentially the same conditions prevail. From the working wavelength of 850 nm we would conclude that the nonlinearity here is even more purely absorptive than in [10] as the dispersive nonlinearity should vanish at the precise band edge wavelength. Then the solitons observed here should rely solely on the absorptive nonlinearity and the otherwise important mechanism of nonlinear resonance [11] would be absent.

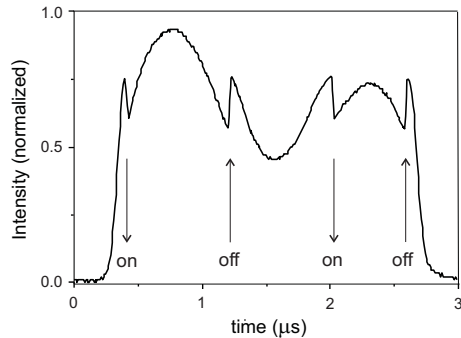


FIG. 5. Repeated switching on and off of a soliton (see text).

Fig. 5 shows fast repeated switching on and off of a soliton. The phase of the address beam was modulated rapidly here by an additional electro-optic phase modulator in the address path at a frequency of 700 kHz and with a phase excursion of somewhat larger than π . Fig. 5

proves again that no slow thermal process is involved in soliton formation or its switch off.

We conclude by noting that these experiments demonstrating the switching of solitons constitute another step towards application of semiconductor solitons to optical information processing e.g. in certain telecom tasks.

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